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THE QUESTION OF MANIPULATOR ACTIVATION BY REVERSIBLE FOLLOW-UP SYSTEMS

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ABSTRACT. The problems of manipulator activation by reversible follow-up systems in each of the drives are discussed. These include the mismatches between input and output coordinates, and the manipulator tongs and their corresponding master arm element, as well as the problems of precision and activation in one drive and the simultaneous operation of all drives.

Most modern master-slave manipulators are activated by reversible follow-up /96 systems (RFS) in each of the drives. This activation method causes the load (forces and moments) acting on the manipulator tongs to be reproduced at the master arm and perceived by the operator with certain distortions. Some of these errors are fundamental in nature and can be attributed to the particularities of the RFS and the kinematics of the manipulator.

The operation of the RFS is accompanied by a definite mismatch between input and output coordinates, and the moment reproduced by it at the input depends on the load, as well as friction and the time lag in the drive units and links in the master and slave mechanical arms. These questions are examined in reference [1].

On the other hand, the manipulator tongs, and the element corresponding to it on the master arm, are mismatched because of the open kinematic circuit in the manipulator arms and the finite stiffness of the drives. The operator must apply forces and moment different from those acting on the tongs in order to balance the mismatched arms. The errors occurring in each RFS, as well as those resulting from the interacting of the RFS when working in open kinematic circuits in the manipulator arms, adversely affect the final activation.

Precision and Activation In One Drive

Figure 1 is a generalized block diagram of the RFS. The input, 2, and output, 4, devices are understood to mean links in the master and slave mechanical arms imparting moments of inertia, J_1 and J_2, respectively, and coefficients of viscous friction c_1 and c_2. Let us designate the moment of inertia of the object of manipulation, 5, imparted to the output link of the drive, 3, as J_0. M_0 is the moment of the external forces acting on the object.

c_0 is the imparted coefficient of viscous friction of the object. Operator 1 creates M_1. Activator 6 measures moment M_2 at the drive output and acts on the input device with moment M'_1. The activator transfer function is $W_2(p)$. The slave arm acts on the object with moment M_2'. The input, x, and output, y, coordinates are linked by

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(1)

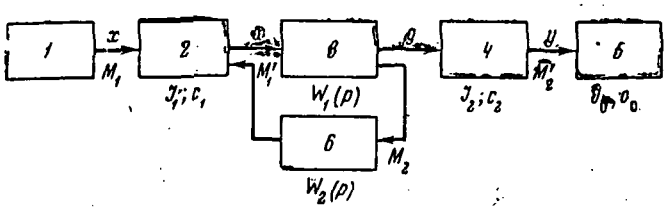

Figure 1.

where the Laplace transforms are designated by vinculums. $W_1(p)$ and $W_3(p)$ are the drive transfer functions with respect to the input coordinate x, and to the drive moment at the output, M_2.

The equation of motion for the output device and the object is

(2)

Substituting into Eq. (1), we obtain

$$x = W_4(p)\,\bar{y} + W_5(p)\,\overline{M}_0, \tag{3}$$

where

$$W_4(p) = \frac{1 - k_2 p W_3(p)(T_2 p + 1)}{W_1(p)};\quad W_5(p) = \frac{W_3(p)}{W_1(p)};$$

$$T_2 = \frac{J_2 + J_0}{c_2 + c_0};\quad k_2 = c_2 + c_0.$$

Eq. (3) gives the possibility of determining the mismatch between the input and output devices for a given law of motion for the object.

Let us now move on to determination of the activation error, which, obviously, is equal to (see Figure 1)

(4)

where K_2 is the scaling factor.

The equation of motion of the input device is

$$(J_1 p + c_1)\, p\bar{x} = \overline{M}_1 + \overline{M}_1; \tag{5}$$

and is, for the object,

(6)

Moments M'_1 and M_2 are linked by

$$\overline{M}'_1 = -W_2(p)\,\overline{M}_2. \tag{7}$$

Substituting Eqs. (5), (6), and (7) into Eq. (4) and using Eq. (2), we obtain

$$\delta\overline{M} = k_1 (T_1 p + 1)\, p\bar{x} + [W_2(p)\, k_2 (T_2 p + 1) - k_0 k_2 (T_0 p + 1)]\, p\bar{y} - [W_2(p) - k_2]\overline{M}_0,$$

where $k_1 = c_1$; $k_0 = c_0$; $T_1 = J_1/c_1$; $T_0 = J_0/c_0$.

Having used Eq. (3), linking x and y, we obtain finally

$$\delta\overline{M} = [k_2 W_3(p)(T_2 p + 1) + k_1 W_4(p)(T_1 p + 1) - k_0 K_2 (T_0 p + 1)]\, p\bar{y} + [k_1 W_5(p)(T_1 p + 1)\, p - W_2(p) + K_2]\,\overline{M}_0. \tag{8}$$

for the activation error in one drive.

We can obtain the mismatch and the activation error for steady-state conditions from general Eqs. (3) and (8).

In the case of a fixed object, for example, and constant moment M_0, /98

where K_1 and K_3 are the amplification factors for transfer functions $W_1(p)$ and $W_2(p)$.

Since most manipulators use a transmission displacement scale of 1:1, $k_1 = 1$, and the mismatch will be determined only by the stiffness of the drive

(9)

The activation error for a fixed object is zero. The activation error when the object is in uniform motion will be $\delta M = (K_2 c_2 + c_1/K_1)\dot{y}$.

The mismatch will depend on the rate of motion and, in the simplest case, ($W_1 = 1$; $W_2 = 1$; $W_3 = -K_3$) will be defined as $\delta y = K_3 (c_2 + c_0)\dot{y} - K_3 M_0$.

Similarly, we can derive expressions for acceleration, for deceleration with

constant acceleration, and the like.

Simultaneous Operation of Drives

Errors in the operator's perception of the load acting on the tongs of the manipulator are caused not only by the imprecise transfer of moment by each of the drives. Another reason for errors is connected with the special features of manipulator kinematics. The mechanical arms have an open kinematic circuit, in which the drives of all the links are interconnected. If in an individual drive the error in moment δM does not directly depend on the mismatch of input and output links δy [see Eq. (8)], then under conditions of simultaneous operation of the drives in a open kinematic circuit the summed effects of these mismatches will directly and adversely affect the activation precision. Indeed, in this case the position of the tongs will differ from the position of the corresponding element of the master arm, and consequently, even in ideal RFS's, which transfer all moments with perfect precision, in order to balance the master arm the operator must apply forces and moments different from those which act on the tongs. As will be shown below, there are some specific positions of the manipulator in which the activation error increases sharply. The fact that the operation of every real RFS is accompanied by its own errors in the transfer of moment only aggravates the situation.

Before moving to an analysis of activation errors, it is necessary to refine certain details. In order to simplify the calculations the present article will examine only the movements of a manipulator in the base plane, that is, in the plane passing through the shoulder S, the elbow El, and the wrist, W (Figure 2). The preceding section examined a linear model of an RFS with constant moments of inertia for the input and output devices. It is impossible to disregard changes in the moments of inertia when operating a manipulator making substantial movements, so the results of the preceding section can be used only when examining manipulator activation in a local area, where it is permissible to consider the moments of inertia constant and it is possible to linearize the dynamics equations. Thus, the results of the following analysis, strictly speaking, are correct near some given position of the manipulator, taken as the initial position. Of course, by considering different initial positions it is possible to cover the entire work space and obtain an idea of the precision of activation in different working operations. The apparatus of the linear theory

of accuracy was used in the analysis [2].

Let the load X, Y, and M act on the object in the manipulator tongs (see Figure 2). Let us designate the moments of the load relative to the corresponding joints as M_S, M_{E1}, and M_W. Then

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(10)

where the designations $l_i \sin y_i = \xi_i$; $l_1 \cos y_i = \eta_i$ $(i = 1, 2, 3)$ are introduced is correct for the slave arm.

All the magnitudes in system (10) will receive certain increments when the transition is made to the master arm of the manipulator. Thus, moments M_S, M_{E1}, and M_W are transferred to the RFS with certain errors δM_S, δM_{E1}, and δM_W. Eq. 8 must be used to find them. Moments M_S, M_{E1}, and M_W are substituted for M_O.

Figure 2.

Mismatch δy_i in the coordinates of the slave arm (y_i) and the master arm (x_i) is found by using Eq. (3). Linearizing ξ_i and η_i with respect to these variables, we find that these parameters for the master arm will take the form $(\xi_1 + \eta_1 \delta y_i)1/k_s$; $(\eta_1 - \xi_i \delta y_i)1/k_s$, respectively, where k_s is the scale factor that includes the different length of the links of the slave and master arms.

And, finally, in order to balance the master arm the operator must apply forces $X + \delta X$, $Y + \delta Y$ and moment $M + \delta M$. Then, for the master arm we derive the equations in increments

(11)

These expression are used to find the operator's error in perceiving the load $(\delta X, \delta Y, \delta M)$ for some initial position of the manipulator, determined by the values of ξ_i and η_i.

The determinant of system (11) equals

$$\Delta = \xi_1\eta_2 - \xi_2\eta_1 = l_1 l_2 \sin(y_1 - y_2). \qquad (12)$$

Since the load on slave arms X, Y, and M is arbitrary, system (11) has no solution in straight elbow positions of the manipulator ($y_1 = y_2$), and near these positions activation errors vanish. This result can be explained by the fact that when the elbow is straight, moment M_{E1} carries no information about the load, a significant part of which is preceived directly by support S, and consequently, distorted information about the load is transmitted by the master arm. /100

Let us illustrate these results by a simple example. Let the manipulator lift a load along a straight line inclined at an angle of 45° to the base plane (see Figure 3, a). The motion mode is quasi-static, that is, static equilibrium conditions are satisfied at any moment. The manipulator is ideal, without limitations in the joints [2]. The initial data: $l_1 = 0.5$ m; $l_2 = 0.3$ m; $l_3 = 0.2$ m; $K_1 = 1$; $K_3 = 0.02$ rad/kgfm; $k_m = 1$; $X = Y = -5$ kgf; $M = -5$ kgfm. Since the mode is quasi-static; $\delta M_S = \delta M_{E1} = \delta M_W = 0$, and the mismatch of the arms, in accordance with Eq. (9), will be $\delta y = -K_3 M_0$.

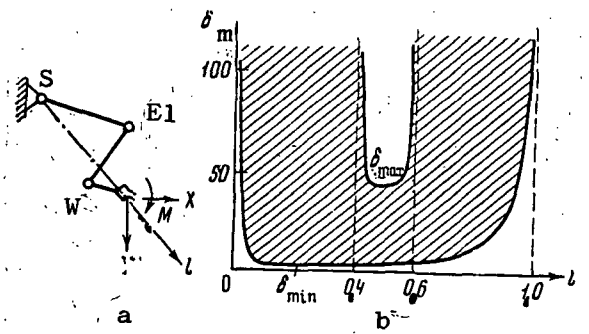

Figure 3. Example of the determination of activation errors. a - diagram of the loading of the manipulator; b - insensitivity zone.

The mean error for this manipulator was determined as $\delta_m = \frac{1}{3}(|\delta X| + |\delta Y| + |\delta M|)$. Maximum and a minimum magnitudes of the mean error when the position of the manipulator is changed within the limits of the service angle [3] were calculated for different points on the straight line examined and over which the load was lifted.

The results of the calculation are presented in Figure 3b. As may be seen, even in the highly favorable case examined, the magnitude of the mean error is great over a substantial section. It is interesting to note the connection of these results with reference [4], where the growth in the errors for mechanisms near the extreme positions was investigated. The straight elbow position in a certain sense may be considered as "extreme", although as applied to manipulators this term demands a more precise definition, since the manipulator, possessing a specific service [3], can occupy

such a position for operations in a larger part of the working volume (see Figure 3).

The analysis made showed that in those cases when an extremely precise activation is required, it is necessary to delineate the working zone which will comprise only a part of the total working space precisely and also to choose the stiffnesses and transfer functions of the RFS on the basis of the condition of ensuring the required activation precision.

REFERENCES

1. Kuleshov, V. S., Lakota, N. A., "Structural and Analytic Presentation of Reversible Follow-Up Systems," V sb: Mekhanika mashin [In collection: Mechanics of Machines], No. 7-8, "Nauka" Press, 1967.

2. Bruyevich, N. G., Tochnost' mekhanizmov [Precision of Mechanisms], OGIZ, 1946.

3. Vinogradov, I. B., Kobrinskiy, A. Ye., Stepanenko, Yu. A., Tyves, L. I., "Features of the Kinematics of Manipulators and Volumes Methods," This collection.

4. Kobrinksiy, A. Ye., "Kinematic Errors of Mechanisms in Near Limit Positions," Trudy seminara po teorii mashin i mekhanizmov [Proceedings of the Seminar on the Theory of Machines and Mechanisms], No. 33, 1950.